TRADE STUDY FOR THE ORBITING TECHNOLOGY TESTBED INITIATIVE TO SUPPORT CODE Y

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Proposal for This Study

The NASA Orbiting Technology Test-bed Initiative (OTTI) will evaluate the effects of real-time space environments on advanced spacecraft technologies. This program is envisioned as leading to a series of low-cost, near-Earth missions in the radiation-harsh Middle Earth Orbit (MEO) environment. This Concept Paper describes potential areas of overlap between OTTI and Code Y program objectives. The trade study identifies spacecraft technologies and environmental parameters to be measured on OTTI in support of Code Y programs and develops specific goals for OTTI flight tests to support Code Y programs.

The areas of common interest for OTTI and Code Y can be divided into three categories. These are: 1) Evaluation of advanced technology and sensors in the radiation environment, 2) Measurement of environmental parameters (such as precipitating electrons) in MEO that affect Code Y missions, and 3) Serendipitous experiments. Broad definitions of the three categories are:

CLASS 1—SENSORS AND TECHNOLOGY TESTING

Complete imaging systems are slated to fly on OTTI for the purpose of evaluating their responses to harsh radiation environments. Optical sensors are rapidly evolving but are especially sensitive to radiation. Yet their performance as remote sensors compels one to use them for space-based Earth observation. OTTI will be available to test the latest imaging technologies in the real space environment. Specific OTTI missions can be adapted to optimally test selected technologies relative to the specifics of the environment such as sun orientation, temperature, directional radiation, etc.

CLASS 2—ENVIRONMENTAL PARAMETERS

The MEO environment plays a part in determining the Earth environment's sensitivity to solar effects. Specifically, the electric fields in the ionosphere, precipitation of auroral particles, and polar cap absorption events affect the Earth's upper atmosphere. The OTTI program is planned to span a decade presenting a useful set of platforms for monitoring environmental factors of interest to Code Y. In-situ measurements of the MEO environment (plasmas, particles, and fields) by OTTI instruments are all of potential value. OTTI environment instruments could be defined to serve both radiation testing and environmental measurement needs for Code Y at a fraction of the cost of a dedicated mission.

CLASS 3—SERENDIPITY

OTTI intends to test a wide variety of commercially available (COTS) and emerging technology components, including whole systems. The OTTI program will identify cross-cutting technologies thereby leveraging off several programs to flight qualify mission enabling technologies, some of which might be of interest to Code-Y. A representative list includes flight data recorders, COTS boards, reconfigurable programming devices, and active pixel sensors.

Environmental measurements by OTTI can be coordinated with simultaneous measurements from the ground and by spacecraft elsewhere in the magnetosphere. These simultaneous measurements may uncover correlations between atmospheric and space phenomena yet to be identified. For example, perturbations in high altitude electron flux measuerd at OTTI might be associated with high latitude-low altitude electron precipitation and aurora .

Background Information

Radiation Effects

There are several effects of the radiation environment on systems: total ionizing dose, displacement damage, single event effects, optical darkening, optical bleaching, and insulator charging. Total ionizing dose and displacement damage are cumulative effects that cause performance degradation of systems with the possibility of eventual system failure. Single event effects (SEE) are induced by a single particle passing through a sensitive node of a device causing local ionization. The effects of SEE and of insulator charging include upsets (bit-flips or noise), latch-ups, functional interrupts, power burn-outs, and gate ruptures. The results range from loss of data and instrument interference to loss of an entire system or spacecraft. Shielding can reduce charging and total-ionizing dose but is less effective in reducing displacement damage or single event effects.

Generally, newer technologies and COTS are more sensitive to one or all of these radiation effects. Ideally, missions should not fly components with known radiation sensitivity, however, the reality of performance requirements compels their use. As a result we have shifted from a *risk avoidance* mode to a *risk management* mode which assumes a level of risk and relies heavily on mitigation techniques. This implies that future missions will assume more risk than in the past.

The OTTI Program

The OTTI (Orbiting Technology Test-bed Initiative) Spacecraft Program is designed to provide an in-space-testing platform for new technologies and systems. The spacecraft orbit will emphasize radiation testing in order to allow future missions to fly in the MEO altitude regions where radiation provides the most severe hazard to many technologies. The OTTI platform can also be used to perform non-radiation tests. The spacecraft will provide power, communications, data storage, digital bus, environmental information, and limited electrical measurement capabilities. Several COTS and emerging technologies have been identified as potential candidates for testing on OTTI missions. Components range from individual devices, such as integrated circuits and optical detectors, to entire systems.

The development of the OTTI program was motivated by the changing market in radiation hardened (rad-hard) devices. Components specifically designed and tested for use in the radiation environment are increasingly unavailable due to decreased investment in the development of rad-hard parts by the Department of Defense (DoD). Rad-hards devices that are available are two to three generations behind in technology and generally will not meet the performance requirements of NASA missions. To meet mission objectives designers are relying on the use of COTS parts and emerging technologies. COTS components are not specifically hardened to radiation effects and, with their high level of integration and high density, some emerging technologies are especially radiation sensitive.

The result of the use of COTS and emerging technologies forces radiation hardness assurance programs to shift to a risk management mode. This shift has serious implications for traditional techniques used for ground testing, risk mitigation and analysis, component screening, etc. For example, enhanced radiation degradation at low space dose rates occurs on some linear bipolar devices. Due to the high cost of ground-based radiation testing, in-space testing is sometimes a cheaper test method for these devices. Also, mitigation of single event effects grows more complex as technologies advance requiring flight validation of testing, prediction, and circumvention techniques. Another issue is the inability to test hybrid and plastic encapsulated parts because test beams cannot fully penetrate the packaging materials. The inability to perform lot acceptance testing on COTS components due to the lack of tracibility is a serious problem that must be addressed.

OTTI was designed to address these issues by identifying and testing (in space) the cross-cutting technologies with potential for radiation tolerance. The goal is to design and validate new approaches to radiation hardness assurance and to validate mitigation techniques. New technologies will have to go from initial design to final flight readiness with a minimum of testing steps, therefore, more effective ground test programs must be designed and flight validated. Table 1 lists some the issues that will be addressed by OTTI.

Table 1
Sample Radiation Effects Issues Addressed by OTTI

Issue	Advantage of Flight Test
LOT ACCEPTANCE TESTING	Validate ground techniques
LOW DOSE RATE	Cheaper to test in space than in the laboratory
SELF HEALING	Control spacecraft operations to recover damaged components
FAULT TOLERANCE	Error correction testing at real error rates
HIGH DATA RATE	Acceptable false bit rate
SENSORS	Establish acceptable degradation, reduced but useful performance in out-years
FAILURE PROBABILITY	Uncertain by factor TEN based on current ground testing, perhaps improved to a factor TWO after OTTI flight tests
BIT LOSS RATE	Measure actual data loss rate in mass data storage
SYSTEM EFFECTS	Tests systems through all operational configurations

Earth Radiation Belts

The morphology of the Van Allen radiation belts is complex. One picture cannot describe the belts. Figures 1 and 2 indicate the yearly total ionizing dose (rads-si) experienced by a component behind two typical levels of radiation shielding for spacecraft in circular orbits as a function of orbital altitude and inclination. A number of proposed or operating spacecraft communication systems are shown as examples. Note that nearly all of those systems have been placed just below the radiation belts so that they would not be exposed to the severe radiation. Very few spacecraft operate in the radiation belts because of the difficulties involved with radiation effects. For complete Earth coverage, operation within the belts is optimum, and for that reason the Global Position System (GPS) is flown within the belts.

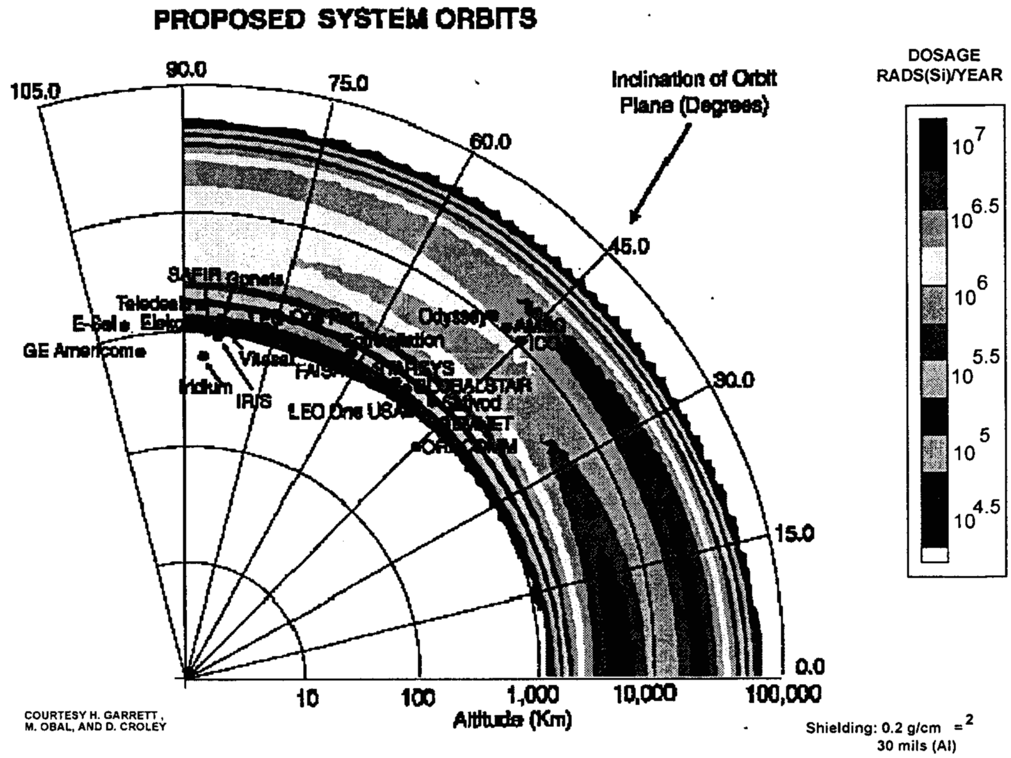

Fig. 1: Yearly radiation dose behind 30 mils aluminum shielding, experienced by spacecraft in circular orbits.

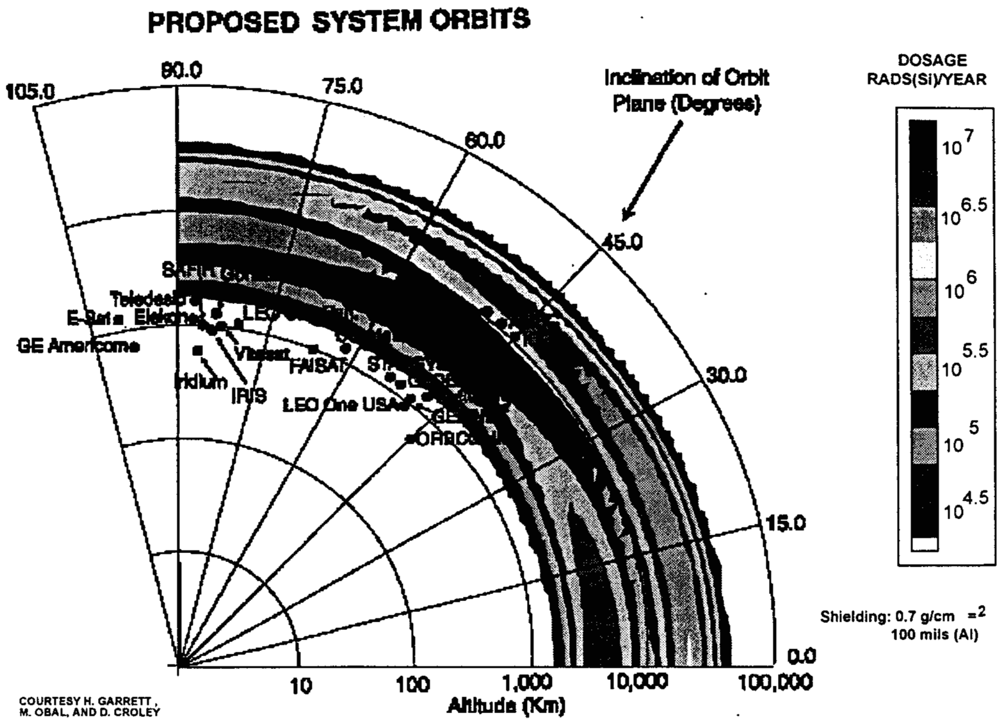

Fig. 2: Yearly radiation dose behind 100 mils aluminum shielding, experienced by spacecraft in circular orbits.

Considering only rads-si, some "soft" devices fail at doses as low as one kilorad-si. Unless they are designed to be hard, most devices fail below 100 kilorads-si. Some technologies cannot be hardened to levels above 100 kilorads-si. Many hardened devices fail at a megarad-si. Thus, operation in the radiation belts provides a severe constraint on the choice of technologies.

Table 2
Inserting Technology into Earth's Radiation Belts
Dose Levels Assume 60 to 120 mils Al Shielding, and Five Years Mission Duration

Orbit	Dose Level	Single Event Effects Hazard
LEO – Low Earth Orbit	100 rads	Low Inclination – Low Polar – Moderate
MEO – Medium Earth Orbit	Megarads	Severe
SPIRAL	Similar to MEO	Severe
GEO – Geosynchronous Orbit	10 kilorads	Moderate
GTO – Geosynchronous Transfer Orbit	100 kilorads	Moderate
MOLNIYA	Similar to GTO	Moderate

Dose in rads-si is not the only parameter of interest. High energy protons (E = .04 to 500 MeV) trapped in the Van Allen belts contribute to both displacement damage and single event effects. The protons peak at about 3000 km and are a serious radiation problem at MEO altitudes. Fluxes of cosmic rays and particles from solar events contribute to the single event effects problem. They have a different spatial distribution than the trapped particles. Their levels increase with increases in both altitude and inclination, with inclination increases being the most important. Protons from solar events are hazardous both in terms of single event effects and long term damage (total ionizing dose and displacement damage). Medium energy electrons, hot and cool plasma, and neutrons can also cause problems.

OTTI will test at MEO:

Assess Failure Rate
New Technologies
Radiation Tolerant System Design
Real Spacecraft Conditions

The Radiation Environment of Low Earth Orbits

Radiation effects are a potential concern for Code Y missions. Although the low earth orbit regime is relatively benign for total dose, newer devices and technologies that fail as low as 1 krad-si are not uncommon. Degradation from displacement damage is also a problem for the long duration low earth orbit (LEO) missions.

Single event effects are also an issue for Code Y missions. It is common for LEO missions to experience problems in a region called the South Atlantic Anomaly. This is the region where the inner radiation belt is closest to the Earth's surface such that low altitude spacecraft pass through it. The Hubble spacecraft turns off some of its systems while passing through this region. The primary cause of these problems is single event effects due to high-energy protons from the radiation belt.

Many Code Y missions use polar orbits to obtain required data coverage. Even though polar missions at low altitudes below 600 km accumulate relatively low doses, they are in a hazardous single event effects environment. The regular traversals over polar regions fully expose satellites to galactic cosmic ray heavy ions and, during solar particle events, to extremely high levels of solar protons and heavy ions. Figure 3 shows that the polar low earth orbit (labeled EOS) encounters a single event effects environment nearly as hazardous as geostationary (labeled GEO)levels.

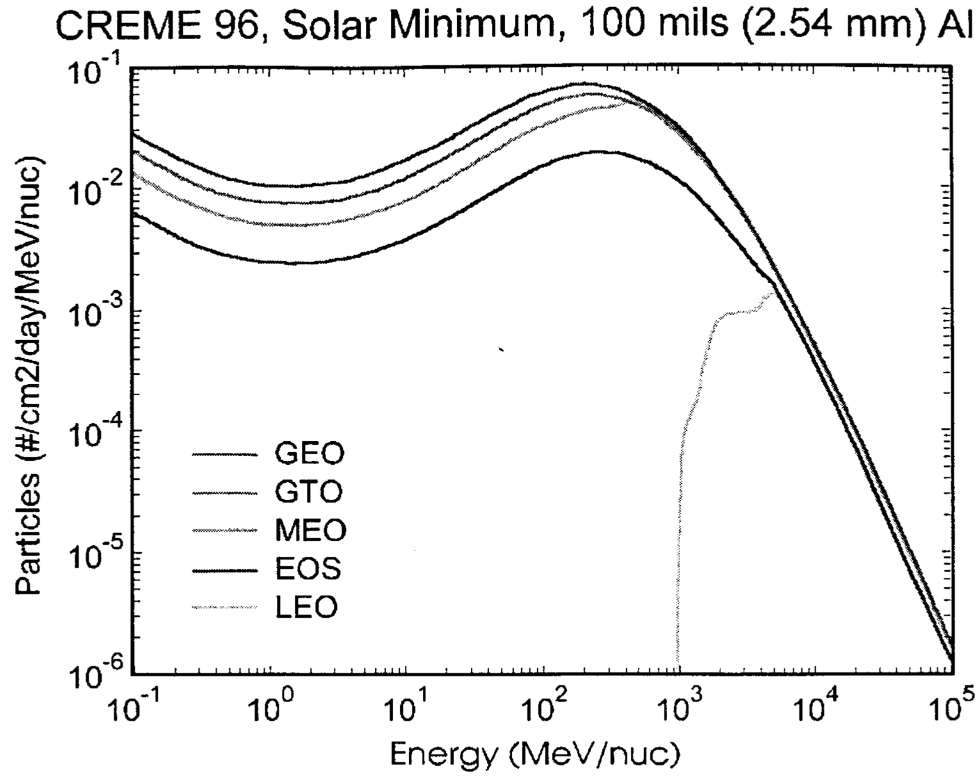

Fig. 3: Galactic cosmic ray heavy ions behind 100 mils aluminum shielding, experienced by spacecraft in circular orbits. EOS is 98deg/705 km, LEO is 39deg/600 km.

Study Results

The study was divided into four parts: microelectronics including memory and computing, photonics, sensors, and micro-electro-mechanical (MEM) devices. Within each part, assessments were made about the radiation vulnerabilities, about the probability that Code-Y programs would use the technology, and about meaningful tests that could be made by OTTI.

Proposed Experiments for Code-Y on the OTTI Mission

A number of experiments are described here that, in our opinion, might be of interest to Code-Y. Many of these experiments are also of interest to other organizations where plans for their implementation may be forming now. But, to our knowledge, the following experiments and technology validations are not planned at this moment. The experiments are summarized in briefing charts.

MICROELECTRONICS

Microelectronic technology is progressing on many fronts in the commercial sector. There is no doubt that the new technologies will be useful on spacecraft. The breakthrough technologies expected in the near future, which appear to provide the greatest gain for Code-Y applications, are summarized. The summary is in the form of a list of proposed OTTI Experiments of the specific technologies.

Breakthrough technology is defined herein as terrestrially used technology which, by itself or in conjunction with other technologies, would enable a factor of 5-10x improvement in one or more critical parameters (such as mass, power, performance, or cost). This improvement is measured relative to technology in currently in use and assumes no significant degradation in other important parameters. Some specific near-term (2002-2003 launch time frame) microelectronics breakthrough technologies that are potentially beneficial to future Code Y wide-band visible and SAR imaging missions have been defined and are listed in the charts. Future Code Y imaging missions will require 1) sensors that gather extremely large quantities of data at very high data rates, 2) mass storage subsystems that temporarily buffer such data, 3) high-speed on-board information extraction and data reduction processing functions, and 4) high-speed data transfer capability over the downlink to earth. The breakthrough technologies in the charts are grouped with complementary technologies into thirteen specific OTTI experiments each of which could potentially provide very significant benefits in terms of the mass, power, performance, and cost impacts of achieving future Code Y mass storage and data processing needs. The thirteen candidate flight experiments are individually discussed in the following paragraphs.

EXPERIMENT 1

Experiment 1 addresses the complementary use of high-density DRAM lithography and low voltage CMOS technologies. Currently, state-of-the-art commercial production lines exist for 64 Mbit DRAM chips using 0.35 micron lithography and 5 volt memory logic levels. This technology has already been qualified for flight missions requiring radiation tolerance. Current 256 Mbit DRAM technology using 0.18 micron technology should be in production shortly after the turn of the century. Projections from the referenced 1997 Electrical Device Miniaturization Study Report (JPL D-14770) and the recently published 1997 Semiconductor Industry Association (SIA) roadmap indicate the near-term availability of a gigabit/die capacity using 0.15 micron feature size and 2 volt memory logic levels. This technology should be available for flight evaluation in the 2002-2003 time frame. If validated, it would provide volatile random access memory capability for Code Y high-speed processing applications at a 5x reduction in mass and a 6x reduction in power relative to state-of-the-art 64 Mbit DRAM technology in current usage.

EXPERIMENT 2

Experiment 2 attempts to exploit the order-of-magnitude performance capability gap between commercial general-purpose processor technology and that available for space applications. High speed (greater than 100 MHz) commercial processors are currently available. For instance, the Intel Pentium II processor operates at a 400 MHz clock rate with a 100 MHz system bus speed. This is more than an order-of-magnitude faster than current radiation-hardened processors used for space.

Current high-speed COTS processors are radiation soft and require high power density. The performance versus power metric is good, but the power required per processor chip is high due to the processor throughput capability. For instance, the Pentium II, when operating at a 400 MHz clock rate, requires about 25 watts. It has a good throughput per watt metric due to the 2 volt logic level and the 0.25 micron feature size, but reflects a high power density per processor die.

Some development prior to flight validation will be necessary to impose individual and system-level processor radiation tolerance characteristics commensurate with a low average power. Use in a distributed fault tolerant architecture with a low-speed radiation-hard controller for executive-level software management of operational modes, architecture configuration, and processor duty cycles will probably be required. With respect to power, 1) efficient heat transfer from each processor die will be needed to accommodate the peak power of each operational mode, and 2) efficient executive level power management in a distributed system architecture will be needed to minimize the average power for each processor. With respect to radiation immunity, component shielding, hardware redundancy management, and SIFT technology will probably be required. These characteristics will have to be implemented without imposing significant impact on the mass and performance (peak throughput) of a processor in a processing system.

If flight validation is successful, this experiment should enable an order-of-magnitude increase in processing throughput commensurate with a lower cost and average power compared with current radiation-hardened general-purpose processors.

EXPERIMENT 3

Experiment 3 involves flight validation in a mid-earth orbit (MEO) space environment of breakthrough packaging technology using 3D subsystem-level stacking of heterogeneous devices. Such 3D mixed-device stacking and interconnection of heterogeneous dice and/or wafers in a single stack has already been demonstrated by several sources in industry. A representative description of 3D mixed device-stacking technology is described in pages 8-12 of the referenced 1997 Electrical Device Miniaturization Study Report (JPL D-14770). Although probably more vulnerable to degrading radiation effects than conventional MCM packaging due to its higher component density, 3D mixed device stacking technology should yield an order-of-magnitude (10x) reduction in mass and size of microelectronics circuits and subsystems relative to conventional MCM state-of-the-art packaging technology in current usage. This should also contribute to lower mission costs by reducing the payload launch weight requirements. It is assumed that future use of low voltage logic levels will minimize power and offset the effects of potential increases in heat density resulting from the higher component density. Thermal problems will also be alleviated by exploiting the inherently high heat transfer efficiency through the carrier substrate layers.

EXPERIMENT 4

Experiment 4 combines several breakthrough technologies with COTS high-speed floating-point digital signal processor (DSP) technology. Projected performance capability from reliable industry sources reflect a potential 2000 MFLOPS throughput at a 1000 MFLOPS/watt performance metric in the 2002-2003 time frame. This assumes low voltage CMOS at levels of 1.2 volts for core logic and 2.0 volts for memory logic. Using a 0.15 micron feature size, a throughput of 2000 MFLOPS should be feasible in a mass of 10 grams.

The foremost problem associated with adapting COTS DSP processing technology to space is that current devices are radiation soft. Application of radiation tolerant standard cell technology to commercial design processes should help resolve this problem. This is currently being pursued by a consortium of the aerospace community. More information is available from a June 1998 OTTI workshop presentation by Jody Gambles from the Institute of Microelectronics of the University of New Mexico.

Radiation tolerant in the context used herein means immunity to single event upsets (SEU), no Latchup (SEL), and resistance to total incident dose (TID) effects on the order of 100 Krads. The SEU and SEL immunity come from circuit design and layout techniques while the total dose performance is inherent in the commercial processes used. Commercial standard cell libraries incorporating these radiation tolerant techniques should be available for DSP implementation and demonstration in the 2000-2003 time frame. Additional potential breakthrough technology enabling increased DSP immunity to radiation effects is thermal spray shielding. This could provide a potential 10x reduction in shield thickness and cost for the same level of immunity compared with conventional shielding technology. More information is available from a June 1998 OTTI Workshop presentation by Ken Heffner of Honeywell.

Successful validation of projected DSP technology in the 2002-2003 time frame could provide a 100x increase in processor throughput relative to floating-point general-purpose spacecraft processors in current usage. Furthermore, it would enable a 5-6x-power reduction relative to current 3.3-5 volt spacecraft technology. Availability of such a DSP processing capability could enable practical on-board processing of raw SAR data from Code Y sensors into image pixels. This could further enable on-board image processing of SAR data for on-board information extraction and data reduction purposes.

EXPERIMENT 5

This experiment combines several breakthrough technologies to achieve an extremely high throughput analog image processing system that requires very low mass and power with good radiation immunity. An initial design is described in the 1995 JPL Second Generation Microspacecraft (SGM) study documentation. It is based on use of multiple ASICs each comprising a fault tolerant synapse and neural image processing array with inherent learning capability. Multiple ASICs are stacked using 3D mixed-device stacking technology (described in JPL D-14770). Each stack is contained in a 10-gram module capable of performing 1024 x 1024 image frame processing at multiple GOPS rates. Related work is published in the 1997 Industrial Electronics handbook. It describes integration of synapse and neural processor arrays with the focal plane of a sensor.

Low-cost radiation-tolerant ASICs could be achieved by using commercial standard cell libraries incorporating radiation immunity techniques. These are currently being developed by a consortium of the aerospace community (June 1998 OTTI Workshop presentation by Jody Gambles of the University of New Mexico). This technology should be ready for a validation flight in the 2002-2003 time frame. If successfully validated, it would enable low-power, low mass analog processing of selected Code Y payload sensor imaging data at TeraOps throughput rates (orders of magnitude faster than current spacecraft payload processing capabilities) for information extraction and data reduction purposes.

EXPERIMENT 6

This experiment is intended to validate the use of commercial laptop computer hard-disk mass storage technology for space applications. The proposed technology provides a nonvolatile storage media that is inherently radiation hard and capable of supporting terabits of storage capacity at multiple Gbps read/write rates while maintaining practical mass, power, and cost characteristics. This technology is described in detail in the referenced NASA white paper dated 5/22/98, which specifically addresses its application to the enhancement of Code Y data acquisition and return capabilities.

Since 1995, COTS hard-disk drive technology has been improving in density and data rate capability at a 60 percent rate each year. Reliable projections indicate that this improvement rate will continue for at least the next 3-4 years. An advanced hard-disk mass storage subsystem architecture scalable to 20 disk drives, is currently being developed this year by Spectrum Astro Corp. with funding support from a government sponsor. Extensive, but cost constrained, ground radiation testing of the COTS 2.5 inch IBM 8GS hard-disk drive being used in the subject mass storage subsystem will be completed later this year. Flight validation of this technology in a MEO space environment should be feasible in the 2002 time frame.

With respect to environmental issues, a COTS hard-disk drive mass storage subsystem must accommodate momentum compensation, hermeticity, vibration isolation, and radiation tolerance to be ruggedized for space applications. Unless the proprietary COTS hard-drive electronics is redesigned for radiation hardness, latchup mitigation techniques will be required to achieve adequate radiation tolerance to latchup of the commercial ASIC's in the drive electronics. Furthermore, some component-level SEU shielding in the drive electronics will be required for operation in the MEO space environment if the commercial disk drive electronics design is not upgraded for radiation tolerance.

Physically, 3x reductions in both size and mass appear realistic relative to alternative state-of-the-art volatile solid-state recorders. Payload metrics for the 2002 time frame reflect 1 Gbit/cc and 250 Gbits/kg.

Considering power, there should be a 3x reduction in peak operating power relative to alternative state-of-the-art solid state recorders. In addition there is no requirement for standby power due to the non-volatility of the storage media.

In terms of cost, a successful flight validation will enable a spacecraft mass storage capability with more than an order-of-magnitude reduction in recurring cost relative to alternative volatile solid state recorder technology. Estimates from reliable industry sources, for a normalized 1000 Gbpds and 1000 Mbps capability, reflect a $200K subsystem recurring cost using hard-disk technology versus a $4M recurring cost using solid state recorder technology.

EXPERIMENT 7

Experiment 7 is based on achieving the COTS high-speed general-purpose processing system goals of the currently ongoing Remote Exploration and Experimentation (REE) project. This effort intends to move Earth-based scalable supercomputing technology into space. It is currently funded by the Office of Space Science (Code S) as part of NASA's High Performance Computing and Communications program. It was started in FY'96 and is currently planned at $102M over 8 years.

By 2003, the REE goal is to fly an on-board computing capability of >300 MOPS/watt scalable to mission requirements. It should be very cost effective requiring no high-cost radiation-hardened processors or special-purpose architectures. Radiation tolerance would be achieved through Software-implemented Fault Tolerance (SIFT) technology. Scalability would be achieved by a simple distributed/parallel architecture of COTS processors.

The REE project needs a testing platform such as proposed for OTTI to validate its concepts. Ground testing cannot provide the duration or the full environment necessary to validate SIFT technology on COTS hardware.

With respect to providing benefits to future Code Y missions, successful flight validation of the REE architecture would provide a 100x improvement in the processing performance versus power metric relative to the Mars Pathfinder Mission. It would also provide an acceptable system-level radiation tolerance using cost-effective COTS hardware technology.

EXPERIMENT 8

Experiment 8 attempts to flight validate a CMOS VLSI technology for producing microelectronic devices that reliably operate at voltage levels far lower than projected by the referenced SIA roadmap. Since the dynamic power consumption of CMOS devices (to the first order) is directly proportional to the square of the operating voltage, this would enable very significant reductions in power consumption. The primary challenge is maintenance of performance with voltage reduction.

The proposed ultra low power (ULP) technology represents a combination of several factors. These include foundry processes, circuit design, and logic architectures. Traditional approaches to achieving lower voltage assume minimization of static leakage currents. The key to the proposed ULP approach is to reduce total energy by balancing dynamic and static power. This balancing approach allows the leakage current to range over many orders of magnitude depending on circuit activity levels. This is accomplished by electronically adjusting the device threshold voltage. This allows maintenance of high levels of performance, even when the operating voltage is lowered to 500 mV or less. The ability to adjust threshold also enables global process variation control within a device die, which improves the lower bound on achievable practical thresholds. Use of such technology to maintain circuit performance should allow ULP CMOS to be practical without having to wait for commercial viability of new lithographic technology.

The ULP development is being led by the University of New Mexico and technically supported by a consortium of aerospace and university partners. Funding support is being provided by both the DOD and NASA. A description of the effort is provided in a June 1998 OTTI workshop presentation by Jody Gambles of the University of New Mexico. A flight experiment to validate 0.5 volt logic using a 0.35 micron feature size should be feasible in the 2002 time frame. If successful, flight validation of the technology would enable a 100x reduction in Code Y microelectronics device power relative to current 5 volt logic devices.

EXPERIMENT 9

Experiment 9 tests the effects of charged particle radiation on a new electronics substrate material. Electronic substrates must be electrical insulators; however, a perfect insulator does not make a perfect substrate. Charged particle radiation deposits unpaired charge and creates paired charge in substrates. The rate of migration of this charge through the substrate is inversely proportional to the electrical resistivity of the substrate. If the radiation flux or the substrate resistivity is too high, charge accumulates. This distorts the ambient electric field, which can adversely affect the performance of electric field sensitive parts (such as field effect transistors), and it can ultimately result in electrostatic discharge. These effects have been observed in polystyrene subjected to space-level radiation.

Amorphous diamond has been proposed as the semiconductor substrate of the future allowing dramatic performance improvements at high circuit densities. Diamond has a thermal conductivity 10X better than traditionally used materials and an electrical resistivity comparable to polystyrene. This makes it potentially very useful for increasing circuit density but a risk to the circuit due to deep dielectric discharging. Ground testing of this effect will be performed at NASA GSFC in FY99.

Diamond can also be processed to provide integrated thermistors in the substrate. Flight testing will both provide performance information about dielectric charging in a flight-like, shielded and grounded configuration and temperature monitoring during thermal cycling using the integrated thermistors.

EXPERIMENT 10

Experiment 10 proposes to test reprogrammable logic devices to identify their radiation tolerance. Reprogrammable devices are a technological evolution stemming from a family of devices including application specific logic devices and field programmable gate arrays. By moving the programming of the device from a hardware basis (physically blowing fuses between logic/memory circuitry) to one more heavily dominated by software (writing and overwriting logic sequences into memory cells), the devices can be modified or repaired while they are integrated in the system configuration. Work has begun to look at producing radiation hard (TID) devices and it may be found that this technology is suitable for porting to a low voltage/ultra low power platform when that technology becomes available.

There are a variety of ways to provide memory based, reprogrammability. The differences between these architectures relate to the circuit devices used, the feature sizes and physical design and how they are interconnected. They will affect the speed at which the part can be programmed and reprogrammed, how much of the space is occupied by overhead structures/information, and the power draw.

The variability between manufacturers' parts makes the assessment of this technology's radiation tolerance important. Device structure and design must be considered when designing a radiation experiment. Characteristics that must be considered and their performance measured are: the memory size/type and logic circuitry ratio, dose rate dependence, reprogrammability, the ability to diagnose failure and to what level of detail, and fault tolerance and the ability to incorporate error correction designs.

The advantages of this technology to missions doing complex, application specific, on-board data processing are that reprogrammable logic has the potential for increasing functionality over its predecessor technologies to the extent that it may replace those technologies in the future. If sufficient circuit density is provided on the die, flexibility with respect to designs that can be implemented and will also enable the user to optimize the part with respect to speed, power and thermal density.

EXPERIMENT 11

Neural Networks and Fuzzy Systems represent two distinct methodologies that deal with uncertainty [10]. Neural networks rely on precise inputs and outputs and a complex problem solving relationship. Fuzzy systems utilize imprecise inputs and outputs encoded in "fuzzy representations and use precise if-then rules to formulate a result. Fuzzy systems are of interest to NASA to solve problems in which the inputs and outputs to the problem set may lack precise definition, but the processes operate in a fashion that lends itself to rule-based decision making. Guidance, navigation, control and pattern recognition are four good examples of such processes.

A number of processors and chip sets have been developed for fuzzy systems. Sasaki, Ueno and Inoue from Kumamoto, Japan have developed a 7.5 MFLIPS Fuzzy Microprocessor chip set using 1.2 um CMOS processes.[12] It can execute 7.5MFLIPS and process 960 rules and 16 input and output variables. Its architecture includes single instruction multiple data (SIMD) execution and logic in memory structures. Such a processor would be capable of performing on-board computing, data handling and control functions for advanced spacecraft architecture.

Two related experiments are being proposed. They assume that the Active Pixel Sensor Instrument will be available. However, similar experiments could be performed using laser radar or some other technique.

EXPERIMENT 11.1 - Fuzzy Three-dimensional Object Recognition

Fuzzy logic has been used in the past for analysis of visual properties and spatial relationships of objects. In this experiment, an Active Pixel Sensor (APS) instrument would be used to capture images of unknown objects and use yet-to-be-tested fuzzy logic circuits to identify and categorize the objects. The rule set would be implemented using field programmable gate arrays and a suitable fuzzy processor would be implemented to serve as a fuzzy inference engine. Ideally, the rule set and inference engine should be implemented in such a way as to allow on-orbit reconfiguration so that multiple algorithms can be tested. This capability could be used to search for ground objects with specific shapes, colors, velocities, etc.

EXPERIMENT 11.2 – Fuzzy Target tracking and Trajectory Prediction

In this experiment, moving objects in the space environment or on the ground would be identified and their trajectory predicted using fuzzy systems. Fuzzy filtering would be implemented into conventional tracking algorithms such as the α–β tracker[13]. Ideally, such an experiment should be conducted on maneuvering and non-maneuvering targets. Success would be measured over a series of orbits and the fuzzy algorithms should be implemented such that the statistical gates that bound the estimated position and velocity of the target can be successively tightened or relaxed.

EXPERIMENT 12

Artificial Neural Networks (ANNs) are most aptly applied to data processing and analysis applications when there is no precise model of underlying processes which are generating the data and/or where there is considerable noise. Some examples are pattern recognition, medical diagnosis, robotics control and high speed communication network traffic control. ANNs are assemblies of elementary networks of interconnected computational nodes (neurons). The algorithm provides "training" and "recall" functions which allow the network to "teach" itself the correct parameter set for the application.

ANNs have been applied successfully to flight image data on the ground including images of clouds, topography and plasma and proton spatial distributions. Simulations and system testing has shown ANNs to be very (95%) tolerant of data bit upsets. These simulations and tests have shown, using a topography pattern recognition application, that systems using commercially available neural processors and non-radiation hard memories are robust in a SEU environment.

The advantages of validating ANN systems to Code Y, is that this technology has the potential for enabling complex data processing on orbit in a hardware environment that has equal or reduced power and memory storage requirements of currently used systems. ANNs have the capability to ignore irrelevant data and to store image data in a compressed form by increasing contrast and reducing spatial resolution. This allows highly processed information to be downloaded, enabling closer to real-time imaging. It may also allow fewer downloads, decreased requirement for bandwidth, a reduced power budget, fewer parts, smaller hardware volume and higher reliability.

This experiment will demonstrate ANNs' robustness in a flight application where actual system noise levels and constrains are present. The experiment will be base-lined using ground-based simulation and testing and would benefit from a comparison between the results of ground-based processing and in flight processing.

EXPERIMENT 13

Commercial-off-the-Shelf (COTS) boards are being assessed for use in programs where the schedule requires rapid procurements and when those schedules and budgets require the use of PC market standard software. From a reliability point of view it is always more desirable to implement (known and) controlled manufacturing processes, reliability enhancing electrical design rules, materials and components which are qualified for use in the applicable space environment (thermal, mechanical, radiation, contamination). When COTS boards are implemented, the conditions driving their use can overwhelm one's ability to design-in reliability and the challenge becomes to estimate and/or increase survivability.

The advantages to Code Y in assessing COTS boards in a spacecraft environment is that it will provide an insertion path for COTS that will not only make flight radiation data available but will demonstrate the level to which COTS boards must be ruggedized or rebuilt to allow them to withstand a satellite environment and total dose effects. There is no question that the use of COTS boards implies an acceptance of a fairly high level of risk, but what is not known is our ability to increase survivability through ruggedization, and the accuracy with which we can predict that level of survivability on the ground.

CONCLUSIONS FOR MICROELECTRONICS

Several candidate microelectronic technologies, when used individually or in combination, appear potentially capable of providing breakthrough 3-100x improvements in critical Code Y payload implementation parameters such as mass, power, performance, and cost. If flight validated on near-term OTTI flight experiments, these benefits could be realized by Code Y missions as early as 2003.

OTTI MICROELECTRONICS TECHNOLOGY INSERTION

POTENTIAL CODE Y BENEFITS – CHART 1

EXP	TECHNOLOGIES	CHARACTERISTICS	VALIDATION BENEFITS	ANALYSIS SOURCE
1	• HIGH-DENSITY DRAM • LOW VOLTAGE CMOS	• 1 GBIT CAPACITY/DIE • 0.15 MICRON FEATURE SIZE • 2 VOLT MEMORY LOGIC	• TIMES 5 COMPONENT DENSITY INCREASE RELATIVE TO CURRENT 64 MBIT, 0.35 MICRON DRAMS (MASS AND SIZE REDUCTION) • TIMES 6 POWER REDUCTION RELATIVE TO CURRENT 5 VOLT SPACECRAFT TECHNOLOGY	• 1997 EDM STUDY REPORT (JPL D-14770) • 1997 SIA ROADMAP
2	• COTS HIGH-SPEED GENERAL PURPOSE PROCESSOR • LOW VOLTAGE CMOS	• 400 MHz CLOCK • 0.15 MICRON FEATURE SIZE • 1.0 VOLT PROCESSOR LOGIC	• TIMES 10 PROCESSOR THROUGHPUT INCREASE RELATIVE TO CURRENT RADHARD SPACECRAFT PROCESSORS • TIMES 10 POWER REDUCTION RELATIVE TO CURRENT 3.3 VOLT SPACECRAFT TECHNOLOGY	• 1997 REE PROJECT DOCUMENTATION (626-30) • 1997 EDM STUDY REPORT (JPL D-14770) • 1997 SIA ROADMAP
3	• 3D MIXED-DEVICE PACKAGING	• SINGLE MODULE CONSISTING OF ASIC I/O DEVICES, PROCESSOR DEVICES, SRAM MEMORY DEVICES, DRAM MEMORY DEVICES • 10 GRAM MASS/MODULE • 6 CC VOLUME/MODULE	• TIMES 10 REDUCTION IN MASS AND SIZE RELATIVE TO CONVENTIONAL MCM PACKAGING	• 1997 EDM STUDY REPORT (JPL D-14770)

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POTENTIAL CODE Y BENEFITS – CHART 2

EXP	TECHNOLOGIES	CHARACTERISTICS	VALIDATION BENEFITS	ANALYSIS SOURCE
4	• COTS DIGITAL SIGNAL PROCESSOR (DSP) • LOW VOLTAGE CMOS • THERMAL SPRAY SHIELDING • RT STANDARD CELL DESIGN PROCESS	• 2000 MFLOPS THROUGHPUT • 10 GRAMS • 2 WATTS PEAK POWER • 1000 MFLOPS/WATT • 1.2 VOLT CORE LOGIC • 2.0 VOLT MEMORY LOGIC • 0.15 MICRON FEATURE SIZE	• TIMES 100 PROCESSOR THROUGHPUT INCREASE RELATIVE TO FLOATING POINT GENERAL PURPOSE SPACECRAFT PROCESSORS IN CURRENT USAGE • TIMES 5 - 6 POWER REDUCTION RELATIVE TO CURRENT 3.3 - 5 VOLT SPACECRAFT TECHNOLOGY • TIMES 10 REDUCTION IN SHIELDING THICKNESS AND COST COMPARED TO AI	• 1997 NEW MILLENNIUM PROJECT (NMP) DOCUMENTATION (DSP CAPABILITY ROADMAP) • 1998 OTTI WORKSHOP PRESENTATIONS
5	• ANALOG NEURAL PROCESSING SYSTEM • 3D MIXED-DEVICE STACKING • RT STANDARD CELL ASIC DESIGN PROCESS	• FAULT TOLERANT SYNAPSE AND NEURAL PROCESSING ARRAYS • MULTIPLE 10 GRAM MODULES EACH CAPABLE OF PERFORMING 1024 x 1024 IMAGE FRAME PROCESSING AT 3 GOPS	• ENABLES LOW-POWER, LOW-MASS ANALOG PROCESSING OF PAYLOAD SCIENCE IMAGING DATA AT TERAOPS THROUGHPUT RATES (ORDERS OF MAGNITUDE FASTER THAN CURRENT SPACECRAFT PAYLOAD PROCESSING CAPABILITIES) FOR DATA REDUCTION AND INFORMATION EXTRACTION PURPOSES	• 1995 SECOND GENERATION MICROSPACECRAFT (SGM) STUDY DOCUMENTATION • 1997 INDUSTRIAL ELECTRONICS HANDBOOK (CRC PRESS) • 1998 OTTI WORKSHOP PRESENTATION

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OTTI MICROELECTRONICS TECHNOLOGY INSERTION

POTENTIAL CODE Y BENEFITS – CHART 3

EXP	TECHNOLOGIES	CHARACTERISTICS	VALIDATION BENEFITS	ANALYSIS SOURCE
6	• COTS HARD-DISK DRIVE MASS STORAGE SYSTEM • RT STANDARD CELL ASIC CONTROLLER DESIGN PROCESS	• 4 DISK DRIVES (SCALABLE TO 20) • 1000 GBIT CAPACITY • 1 GBPS READ/WRITE RATES • <4 KG MASS • <12 WATTS POWER	• RADHARD NONVOLATILE STORAGE MEDIA • TIMES 10 REDUCTIONS IN MASS, POWER, AND COST RELATIVE TO ALTERNATIVE VOLATILE SOLID-STATE RECORDER (SSR) TECHNOLOGY	• 1998 NASA GENERATED WHITE PAPER • 1998 OTTI WORKSHOP PRESENTATION
7	• COTS HIGH-SPEED GENERAL PURPOSE PROCESSING SYSTEM • SOFTWARE IMPLEMENTED FAULT TOLERANCE (SIFT)	• SCALABLE DISTRIBUTED/PARALLEL FAULT TOLERANT ARCHITECTURE OF COTS HIGH-SPEED GENERAL PURPOSE PROCESSORS • SIFT TECHNOLOGY FOR RADIATION TOLERANCE • 300 MOPS/WATT PERFORMANCE METRIC	• TIMES 100 IMPROVEMENT IN PERFORMANCE VERSUS POWER METRIC RELATIVE TO MARS PATHFINDER MISSION • NO HIGH-COST RADIATION HARDENED PROCESSORS OR COMPLEX SPECIAL-PURPOSE ARCHITECTURES REQUIRED TO ACHIEVE ACCEPTABLE SYSTEM-LEVEL RADIATION TOLERANCE	• 1997 REE PROJECT DOCUMENTATION (626-30)
8	• ULTRA-LOW POWER (ULP) CMOS DEVICES	• 0.5 VOLT LOGIC • 0.35 MICRON FEATURE SIZE • ADJUSTABLE THRESHOLD VOLTAGE	• TIMES 100 REDUCTION IN POWER RELATIVE TO CURRENT 5 VOLT SPACECRAFT TECHNOLOGY DEVICES	• 1998 OTTI WORKSHOP PRESENTATION

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POTENTIAL CODE Y BENEFITS – CHART 4

EXP	TECHNOLOGIES	CHARACTERISTICS	VALIDATION BENEFITS
9	• CVD Diamond Substrates	• High thermal conductivity • High strength • Integrated thermistors can be used to collect thermal data	• Enables high circuit density • Enables use of hot COTS parts and assemblies
10	• Reprogrammable Logic	• Higher circuit density • Lower level of (on chip) device integration	• Enables in-flight modification and/or repair of computing circuitry • Allows circuit implementations to match commercially available components.
11	• Artificial Neural Networks	• Implemented with commercially available processors, co-processors and non-rad hard memories • Self-healing and very fault tolerant. • Is "taught" how to perform for a specific application and can ignore irrelevent data	• Will enable in-flight data processing without the need for increased power and additional memory. • Will enable more real-time imaging by reducing the bandwidth required for downlinks
12	• Fuzzy Logic	• Expert system • Applies to problems with imprecise boundary conditions • Rule based system	• Reduce man-in-the-loop operations • Can be used to predict trajectories for oncoming particles
13	• COTS Boards	• Much reduced procurement cost • High level of availability • Lower software costs	• Provide a COTS insertion path for missions faced with cost and schedules needs driving the use of COTS • Provide data for terrestrial modeling and prediction of survivability

PHOTONICS

Like microelectronics, photonics is advancing in many areas. The photonics technologies that will have the greatest benefits for Code Y applications are summarized below as a list of proposed OTTI experiments.

EXPERIMENT 14

Experiment 14 combines Vertical Cavity Surface Emitting Laser (VCSEL) technology with Polarization Maintaining (PM) optical fibers to produce an extremely high speed, high performance, low power, Electromagnetic Interference (EMI) resistant data bus. The Vertical Cavity Surface Emitting Laser (VCSEL) is an emerging technology that has important applications in high-speed, multiplexed communications. It can operate switching rates beyond 2 GHz and can function at very low power levels.

Heavy particles such as protons or neutrons carry sufficient momentum to be efficient at disrupting the crystal lattices of VCSEL's. The result is a decrease in photon emission and the efficiency of light emission. There is little data on the stability of the newest PM fibers in a radiation environment, and it is known that a radiation can induce scintillation in an optical fiber producing erroneous data.

A high data rate communication experiment is proposed to demonstrate the performance of commercially available VCSEL arrays coupled with PM fiber.

EXPERIMENT 15

Experiment 15 combines Bragg gratings used as optical sensors with erbium doped fiber amplifiers. This will efficiently integrate sensing and amplfying functions in a single technology. While Bragg gratings have been used in optical sensors as notch filters and narrow band filters, displacement damage that occurs in a high radiation environment could create a shift in the wavelengths that the gratings reflect or filter, compromising functionality in MEO. Optical fiber amplifiers, such as erbium doped fiber amplifiers, are increasingly being used in space applications despite the fact that these devices do not degrade linearly in a radiation environment. The long term behavior of these devices in radiation environments needs to be established.

CONCLUSIONS FOR PHOTONICS

Several photonic technologies seem to have potential benefits to Code Y missions. They appear capable of providing breakthrough 3-100x improvements in critical Code Y payload implementation parameters such as mass, power, performance, and cost. If flight validated on near-term OTTI flight experiments, these benefits could be realized by Code Y missions as early as 2003.

OTTI PHOTONICS TECHNOLOGY INSERTION

POTENTIAL CODE Y BENEFITS

EXP	TECHNOLOGIES	CHARACTERISTICS	VALIDATION BENEFITS
14	• Vertical cavity surface emitting laser • Polarization maintaining fiber	• High speed (2 Gbps+) • Low power • EMI Resistant	• Times 10 to 20+ increase in speed • Lower data rates
15	• Bragg gratings • Erbium-doped fiber amplifiers	• Increased data resolution • Increased data rate • Low power • EMI resistant	• Times 10 to 20 increase in speed • Lower data errors

SENSORS

The Active Pixel Sensor (APS) is a key enabling technology for imaging and remote sensing for space applications. APS combines the best of both charge coupled and charge injection (CCD and CID) imagers. They can be fabricated in standard CMOS processes and provide for the integration of an amplifier at each pixel. They can be random-access addressed and the amplifier per pixel allows for adaptive imaging and compensation. APS is accomplished at much lower power levels than standard CCD images and power savings up to 2 orders of magnitude are possible.

The JPL Center for Space Microelectronics Technology has developed a number of APS products for space including a star tracker, smart vision with programmable neural processor, multi-resolution image sensor, and charged particle spectrometer. JPL has also developed a charged particle spectrometer for trapped electrons and protons in low earth orbit using a form of APS. This instrument was a part of the STRV-2 mission.

Although APS systems provide high quality images at low cost, existing systems do not yet perform motion detection and normal video output simultaneously. Japanese researchers at Nikon have reported on motion detection integrated with the APS. The JPL smart vision system is also reported to be capable of performing motion detection and motion estimation.

EXPERIMENT 16

This experiment would consist of flying the JPL CPS32 Active Pixel Sensor instrument and accumulating data on the performance of the instrument in the OTTI orbit. The previous space exposure for the instrument was a minimal 10krads, so this would allow additional total dose exposure data to be accumulated.

MICRO-ELECTRO-MECHANICAL DEVICES (MEM)

A two-day Workshop on MEM Technology was reviewed. No devices appeared to need OTTI Code-Y attention at this time.

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